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FISSION AND RADIATIVE CAPTURE CROSS SECTION OF 25 FOR THERMAL NEUTRONS

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ABSTRACT

The fission cross section of 25 has been compared with the activation cross sections of Au^{197} and Mn^{55}. The detection of these radioactive monitors was calibrated by the method of coincidence counting. The results are;

$$(\sigma_f/\sigma_{Au})_{th} = 5.37 \pm 0.32$$

$$(\sigma_f/\sigma_{Mn})_{th} = 42.1 \pm 2$$

From these

$$(\sigma_f)_{kT} = 526 \pm 30 \times 10^{-24} \text{ cm}^2$$

From this and the absorption values $\sigma_a(25) = 645 \times 10^{-24}$ cm^2 and $\sigma_a(Au) = 94 \times 10^{-24}$ cm^2, the ratio of competing radiative capture to fission appears to be

$$(\alpha)_{kT} = 0.23 \pm 0.08.$$

FISSION AND RADIATIVE CAPTURE CROSS SECTION OF 25 FOR THERMAL NEUTRONS

INTRODUCTION

Precise measurements of the total cross section of 25 for removing thermal neutrons from a beam have been made by Fermi [1] and by McDaniel et al [2].

In the past it has been generally assumed that the only process available for removal was the (n,f) process. Doubts were cast on this assumption by a) the sharp fission resonances observed by McDaniel [2] which indicate that the compound nucleus 26* has a sufficiently long life to permit appreciable competition by (n,γ); b) relative measurements by Farwell and others [3] of activation cross sections for neutron-induced radioactivities compared with $(\sigma_f)_{25}$, which seemed to indicate consistently higher results than obtained by other methods, when the known absorption cross section of 25 was used. It was pointed out that these difficulties would be removed if one could demonstrate the existence of a competing process, such as (n,γ) with a probability comparable with that of (n,f). The ratio of these probabilities shall be called α.

The purpose of this investigation is to elucidate this point by meas-

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1) Fermi, CP-1389.

2) Anderson, Lavatelli, McDaniel and Sutton, LA-91.

3) LAMS-48.

uring $\sigma_f'(25)/\sigma_r'(Au)$ and comparing it with the value of $\sigma_a'(25)/\sigma_a'(Au)$ obtained from transmission measurements. Eliminating $\sigma_r'(Au)$, which is of course assumed equal to $\sigma_a'(Au)$, one obtains $1 + \alpha = \sigma_a'(25)/\sigma_f'(25)$.

In these formulae σ_a' denotes the total absorption cross section, i.e. the sum of the cross sections for competing processes.

In Part A we discuss the absolute measurement of the neutron flux, in Part B the determination of the counter efficiency, in Part C the fission counting, and in part D the results of the observations are calculated and discussed.

A. ABSOLUTE MEASUREMENT OF THERMAL NEUTRON FLUX

1. General Considerations

Most measurements of slow neutron activation cross sections involve expressions of the type

$$nv = n_P/\sigma_P' \epsilon_P N \qquad (1)$$

where n_P is the number of induced processes observed per unit time,

ϵ_P is the efficiency of the instrument used for observing the process P,

σ_P' is the cross section of a detector atom for this process,

N is the number of atoms of detector material.

This equation may be solved for σ_P' if the neutron flux nv is known. In order to put such measurements on an absolute basis we must have at least one absolute standard for which σ_P' is known from independent measurements. These latter usually consist in transmission experiments, which determine the total cross section for removal of a neutron, σ_a'. If there are processes P' alternative to P, for which $\Sigma\sigma_{P'} = \alpha\, \sigma_P'$, then $\sigma_P' = \sigma_a'/(1 + \alpha)$. If the detector

is a mixture of isotopes, P' may, of course occur in a different isotope than P. Applying Eq. (1) both to a standard A and an unknown B, which has no competing process, we can eliminate nv and get

$$\sigma'_{PB} = \sigma'_{aA}\, n_B\, N_A\, \epsilon_A / (1+\alpha_A)\, n_A\, N_B\, \epsilon_B \qquad (2)$$

A suitable standard detector must permit accurate determination of all relevant quantities in Eq. (2). This means a) $\sigma'_a \gg \sigma'_s$, σ'_s being the scattering cross section, to permit accurate transmission measurements. Also σ'_a should vary in a simple way with neutron velocity in the thermal region, preferably as 1/v. b) α should be negligibly small or well known from other experiments. c) P_A should be of such a nature that ϵ_A can be determined accurately. d) The quantity of detector material used must be such that it can be accurately weighed or otherwise determined.

The process most commonly used as absolute standard is $B^{10}(n,\alpha)$. It satisfies condition a) above very well, and, when used as BF_3 gas, also conditions c) and d). When it has to be used as foils, however, c) and d) require considerable care [4]. Condition b) is generally assumed to be satisfied, although radiative capture by either B^9 or B^{10} cannot be entirely excluded as a remote possibility. A similar situation exists with respect to Li (n,p).

In many respects the process 25 (n,f) seems to have desirable properties as absolute cross section standard, because of the relative ease of experimental procedure and because it lends itself readily to measurements at higher energies. A number of activation cross sections have been measured by comparison with 25. However, when the value $(\sigma'_{25})_{kT} = 645$, found from transmission ex-

4) Bailey, Blair and Russell, LA-90.

periments [1), 2)] was used for σ_f', the resultant values of a number of cross sections for induced radioactivities were consistently higher than those found by other methods [3)]. It was pointed out by Farwell and Segre[3)] that this might be due to another process competing with the fission. Since then $(\sigma_f')_{25}$ has been compared with B (n, α) by Bailey et al [4)] and with Li (n,p) by Fermi et al [5)] and by Bailey. Both authors find σ_f' smaller than σ_a' found by transmission, the ratio being 1.21 (Fermi) and 1.16 (Bailey) respectively.

It seemed desirable to measure σ_f' by comparing with a capture process leading to a radioactive isotope, both because the possible difficulties of the other methods could be checked by an independent method and because the great convenience of the use of radioactive monitors led us to hope that the method might lend itself to absolute measurements.

2. Induced Radioactivities as Absolute Standards

The neutron induced activation of materials such as In, Mn, and Rh, has been used for a long time for the relative measurement of thermal neutron flux. In order to extend the method to absolute measurements we must find suitable substances satisfying conditions a) to d) of Section 1. These conditions limit us to substances having only one isotope (condition b), a large cross section (a) and for which the induced radioactivity shows a fairly simple and well understood disintegration scheme (c) and no isomeric states (b). Unfortunately indium, which has a very convenient cross section and half life is ruled out by conditions b) and c). In fact the only substance satisfying all conditions and whose cross section has been measured accurately by transmission seems to be Au^{197}. We have therefore used gold as our absolute standard. A few measurements were also made using Mn^{55}, but its cross section is, at present not sufficiently well

5) Fermi, CP-1531.

[redacted]

known to yield the desired accuracy.

If a substance yielding a radioactive product with decay constant λ is exposed to neutrons for a time T and the rate of production of active atoms is $n(t)$, then the rate of decay at the end of bombardment is

$$n' = \lambda \int_0^T n(t) \exp(-\lambda t) dt \qquad (3a)$$

which may be solved for n_0 if n is constant.

$$n = n^0 / \left[1 - \exp(-\lambda T) \right] \qquad (3b)$$

which becomes, for very long exposure, $n = n^0$. For very short exposures, it is

$$n = (n^0 / \lambda T)(1 - \tfrac{1}{2}\lambda T)^{-1} \qquad (3c)$$

This means that any error in λ enters directly into n_A Eq. (2) unless $T \gg 1/\lambda$ which is impractical in the case of Au^{198}. On the basis of published results and of a number of measurements of our own we used $\lambda_{Au} = (1.78 \pm 0.02) \times 10^{-4}$ min^{-1}. In the case of Mn^{56} we used the value $\lambda_{Mn} = (4.46 \pm 0.04) \times 10^{-3}$ min^{-1}, confirmed by many experimenters.

The capture cross section of gold has been measured with velocity selectors by Fermi et al [6] and by McDaniel [7]. The latter author also showed that it obeys the 1/v law in the thermal region. The values for a neutron velocity of 2.2×10^5 cm/sec are 93 (Fermi) and 94 (McDaniel) $\times 10^{-24}$ cm^2. We have

6) Fermi and Marshall, J., CP-1255.

7) Anderson, Lavatelli, McDaniel and Sutton, LA-93.

[redacted]

used the value $(94 \pm 2) \times 10^{-24}$ cm^2.

In the case of Mn, no velocity selector measurements are available because of the small value of the cross section. We have used the value 13×10^{-24} cm^2 ± 10% as the most probable value for $(\sigma)_{kT}$ from a number of measurements [8].

There are, at present, essentially three methods for the determination of the number of disintegrations taking place in a source of beta rays. A. Complete detection, involving a "4π counter" of some type. It is applicable if there is at least one electron per disintegration and no delayed radiations. The use of extremely thin sources makes it difficult to satisfy condition d), Section 1 and is generally somewhat inconvenient. B. Calibration by coincidence counting. This method is discussed in Section 3. It is applicable if the disintegration scheme is reasonably simple and its relevant phases well understood, and if some γ rays are emitted. C. Calibration by natural sources. This refers a standard ultimately to alpha ray counting. It is applicable when there is one and only one electron per disintegration and if the beta rays are fairly penetrating. We used methods B and C for these measurements in the case of gold, attaching more weight to the results of the more accurate method B, which was the only one used in the case of Mn.

8) Kubitschek, CP-1389.

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B. DETERMINATION OF COUNTER EFFICIENCY BY COINCIDENCES

3. Method

The principle of the method has been discussed by Dunworth [9]. Consider, first, the simple disintegration scheme shown in Fig. 1A, with a simple beta ray spectrum accompanied by a single gamma ray. If such a source is placed between a beta and a gamma ray counter in an arrangement such as shown in Fig. 2 which allows us to count pulses in each counter as well as coincident counts, then we have for these counting rates

$$n_\beta = n_o \epsilon_\beta \tag{4a}$$

$$n_\gamma = n_o \epsilon_\gamma \tag{4b}$$

$$n_{coinc} = n_o \epsilon_\beta \epsilon_\gamma \tag{4c}$$

where n_o is the rate at which disintegrations take place and the ϵ's are the net efficiencies of the two counters. These equations can be solved for the efficiencies and for n_o. If the disintegration scheme is more complicated we can write more general formulas, provided none of the radiations are delayed. If the various modes or "paths" from the initial to a final state have relative probabilities f_k we have

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9) Dunworth, Rev. Sc. Inst., 11, 167 (1940).

[redacted]

$$n_1 = n_o \sum_k (f_k \sum_i \epsilon_i) \tag{5a}$$

$$n_2 = n_o \sum_k (f_k \sum_i \epsilon'_i) \tag{5b}$$

$$n_{coinc} = n_o \sum_k (f_k \sum_i \sum_j \epsilon_i \epsilon'_j) \tag{5c}$$

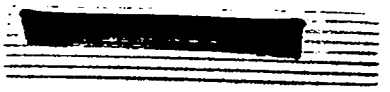
The efficiencies of the two counters for the same radiations are distinguished by the prime and the summations over i and j extend for each k over the radiations involved in the k'th mode of decay. The application of these formulas to the schemes shown in Fig. 1B and 1C will be discussed in later sections. They assume that for each k and each counter $\epsilon_i \epsilon_j$ $(i \neq j)$ is always negligible compared to one of the two ϵ's involved.

4. Apparatus

Two sets of counters were used in these experiments. All of the counters were of the "fast" argon - alcohol type. Fig. 2 shows the arrangement used for actual calibration, seen from above. The bell type beta ray counter had a mica window about 5 mg/cm^2 thick and the gamma ray counter was made of a brass tube on the inside of which a thin film of bismuth was plated to increase the efficiency for low energy gamma rays. The sources, discs 2.07 cm in diameter, were mounted on the brass slide with "scotch tape". For some preliminary measurements a pair of thin walled aluminum counters was used, one with its axis vertical, the other horizontal. One of them could be used as gamma ray counter by sliding a thin lead cylinder over it. Sources were mounted between the two counters on a brass slide similar to the arrangement shown in Fig. 2. Both sets of counters were enclosed in a lead shield 2 to 4 inches thick.

It is very important that the counters used should not show double or "satellite" pulses which are usually due to inadequate quenching of the discharge. Inspection of Eqs. (4) shows that such multiples, which do not, of course, coincide with other radiations, would lead one to underestimate the efficiencies of the counters. Three tests were made for the presence of "satellites". The pulses were observed on an oscilloscope and showed no signs of doublets. The counters had plateaus which were flat (less than 2 percent rise) over a range which initially exceeded 100 volts. This is a good indication of adequate quenching. The third test consisted in the following experiment. A source of RaE was placed on one side of the pair of thin-walled counters and these were masked in such a way that all of the beta rays entering the second counter had to pass through the first. Since a counter will record every particle entering it, provided the counting rate is not too high, the coincidence counting rate should be equal to the counting rate of the second counter. Failure to be so would indicate multiple counts in the second counter or failure to detect all coincidences, because of time delays etc. It was found that the two counting rates were equal unless the gate of the coincidence circuit was chosen too narrow. The resolving time used in practice was 4 μsec. Once it was shown that both thin-walled counters behaved properly, the result could be extended to the other pair of counters by showing that the number n_o in Eq. (4) was found the same in both pairs if the same source was used.

It is easy to see that Eqs. (4) and (5) require that the efficiency of at least one of the two counters should be independent of the part of the source from which the radiation is emitted. It was ascertained that this condition was always fulfilled for the gamma ray counter by noting that the counting rate due to a given source was the same whether it was spread out over the entire area of

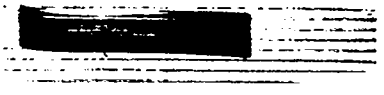


2 cm diameter or folded into a small square at the center. Also the thickness of all sources was such that self absorption of gamma rays was negligible.

5. Disintegration Scheme of Au^{198}

The radiations of Au^{198} have been studied by a number of workers, with results which are in general consistent. The scheme shown in Fig. 1B is based on unpublished work done at MIT. Some of the experiments which have a direct bearing on the validity of our counter calibration were as follows. Orbital electron capture was shown to be absent or at least rare because all of the X-rays were found to coincide with beta rays and are therefore due to the internal conversion process. The probable error of this experiment is not available but was probably fairly large. The effect of orbital electron capture would be to introduce an α into Eq. (2). Since the only conversion electrons of sufficient energy to penetrate the beta counter are the 5 percent due to the 410 kev gamma ray, as shown in the beta ray spectrometer, and these coincide with the disintegration beta rays (see below), there are no delayed electrons which could affect our calibration. It was also shown that the very soft conversion electrons coincide with the beta rays, by placing a source directly inside a counter. It is extremely unlikely that any delayed gamma ray should fail to be internally converted. Studies of secondary electron spectra showed no trace of any gamma rays not accounted for in Fig. 1B. We may conclude that there are no delayed radiations. To determine the number of conversion electrons entering the beta ray counter a thin ($5 mg/cm^2$) source of gold was placed between the two thin-walled counters. Only conversion electrons due to γ_1 are energetic enough to enter the counter. It is easy to show from Eq. (5) that, to a sufficient approximation

$$n_{coinc}/n_{\beta} = 2a_1 \epsilon_{conv} \qquad (6)$$



if the two counters are reasonably symmetrical. Here a_1 is the conversion coefficient as indicated in Fig. 1B. The fraction of all particles which are conversion electrons is given by $a_1 \epsilon_{conv}/\epsilon_\beta$. ϵ_β is found from a beta-gamma coincidence experiment for the particular geometry used. The result of the experiment was that 6 ± 1 percent of the particles were conversion electrons, in good agreement with the value 5 percent found in the spectrometer.

6. Calibration of Gamma Ray Counter for Au^{198}

When enough absorber is placed between the source and the beta counter (Fig. 2), so that no conversion electrons but only the harder beta rays can enter the counter, Eqs. (4) may be applied to the observations with minor corrections. The counting rate of the beta counter (4a) must be corrected for the effect of the gamma rays on this counter; this also gives rise to a very small term of gamma-gamma coincidences in Eq. (4c). Finally, instead of ϵ_γ in Eqs. (4b) and (4c), we should use η_γ the total average efficiency for detecting γ_1, γ_2, or the X-rays accompanying the internal conversion. By Eq. (5b)

$$\eta_\gamma = (1-a_1)\epsilon_{\gamma_1} + (1-a_2)\epsilon_{\gamma_2} + (a_1+a_2)\,\epsilon_x$$

This is, however, a purely formal change since η_γ is the very efficiency we wish to determine and enters into the equation just as does ϵ_γ in Eqs. 4. In fact, the term in ϵ_{γ_1} constitutes over 95 percent of the total since the other, very soft, radiations are strongly absorbed in the counter wall. In the following we show a typical set of data, expressed in counts per minute.

Beta counter		Coincidences	
Total n_1	10700	Total	12.30 ± 0.3
Gammas	700	Chance	1.44 ± 0.2
Background	30	Gamma-gamma	0.10 ± 0.1
Net n_β	9970 ± 300	Cosmic Ray etc.	0.74 ± 0.07
		Net $n_{\beta\gamma}$	10.0 ± 0.4
Gamma counter			
Total n_2	1103	$\eta_\gamma = n_{\beta\gamma}/n_\beta = (1.00 \pm 0.05) \times 10^{-3}$	
Background	55		
Net n_γ	1048 ± 15	Absorber: 158 mg/cm^2 Al	

Several runs were made with various source strengths and absorber thicknesses. Altogether 10,000 coincidences were counted. The final result is

$$\eta_\gamma = (1.00 \pm 0.02) \times 10^{-3}$$

The observed spread of the data was consistent with the calculated counting statistics.

7. Calibration of Beta Ray Counter for Au^{198}

Because the sources used in the final cross section measurements were rather weak it was necessary to calibrate the beta ray counters without absorber. The efficiency desired is not ϵ_β entering the coincidence equations but η_β, including the effects of beta rays, conversion electrons and gamma rays on the beta counter. This quantity is obtained by comparing the counting rate produced

by the same source in the calibrated gamma counter and in the beta counter. However, since these two counting rates differ by a factor of about 200 it was necessary to use intermediate steps, in which the counter was calibrated with absorbers and then a weaker source used to compare the efficiency with and without absorber. As an alternate procedure the same source was counted first in the gamma ray counter and then allowed to decay until it could be counted in the beta ray counter. This involves accurate knowledge of the decay constant. The main source of error in these measurements is the difficulty in replacing the source accurately in the holder. The thin leaves used are not always perfectly flat. Also their thickness varies by as much as 15 percent in manufacture. Therefore the observed spread of the data was used instead of the calculated counting error. The counter shown in Fig. 2 was calibrated for sources of about 5 mg/cm^2 backed either by a microscope cover slip (η_g) or by cellophane tape (η_c). Another, similar counter, called counter B, was calibrated for the same sources with cellophane backing. The result, allowing also for the probable error in the primary gamma ray calibration, is

$$\eta_g = 0.206 \pm 0.008, \qquad \eta_c = 0.178 \pm 0.008, \qquad \eta_b = 0.250 \pm 0.012$$

The difference between η_g and η_c is due to reflection of the beta rays by the glass and, possibly to a slightly different location of the source with the two types of mounting.

8. Disintegration Scheme of Mn^{56}

Fig. 1C shows the disintegration scheme given by Elliott and Deutsch [10].

10) Elliott and Deutsch, Phys. Rev., 64, 321 (1943).

Experiments leading to its establishment and references to other papers are given by these authors.

9. Calibration of Gamma Counter for Mn^{56}

Writing Eqs. (5) for the disintegration scheme of Mn^{56} we obtain

$$n_1 = n_o(f_1 \epsilon_{\beta_1} + f_2 \epsilon_{\beta_2} + f_3 \epsilon_{\beta_3}) + n_o(f_1 \epsilon_{\gamma_1} + f_2 \epsilon_{\gamma_2} + f_3 \epsilon_{\gamma_3}) \tag{7a}$$

$$n_2 = n_o(f_1 \epsilon'_{\gamma_1} + f_2 \epsilon'_{\gamma_2} + \epsilon'_{\gamma_3}) = n_o \eta_\gamma \tag{7b}$$

$$\begin{aligned} n_{coinc} &= n_o \left[f_1 \epsilon_{\beta_1} (\epsilon'_{\gamma_1} + \epsilon'_{\gamma_3}) + f_2 \epsilon_{\beta_2} (\epsilon'_{\gamma_2} + \epsilon'_{\gamma_3}) + f_3 \epsilon_{\beta_3} \epsilon_{\gamma_3} \right] \\ &\quad + n_o \left[\epsilon_{\gamma_3} (f_1 \epsilon'_{\gamma_1} + f_2 \epsilon'_{\gamma_2}) + \epsilon'_{\gamma_3} (f_1 \epsilon_{\gamma_1} + f_2 \epsilon_{\gamma_2}) \right] \\ &= n_{\beta\gamma} + n_{\gamma\gamma} \end{aligned} \tag{7c}$$

According to Fig. 1C, $f_1 = 0.15$, $f_2 = 0.25$, $f_3 = 0.60$. As in the case of gold, the second term in (7a) and in (7c) is due to the effect of gamma rays on the beta counter and can be corrected for by observations in which sufficient absorber is used to remove all of the beta rays. The three ϵ_β's will depend on the amount of absorber and on the source thickness. When a very thin source and no absorber is used the three efficiencies become equal. In this case we may write, dropping the gamma ray terms, which can be corrected for

$$n_1 = n_o \epsilon_\beta$$

$$n_{coinc} = n_{\beta\gamma} = n_o \epsilon_\beta \eta_\gamma \qquad \text{or} \qquad \eta_\gamma = n_{\beta\gamma}/n_1$$

[redacted]

Fig. 3 shows the value of $n_{\beta\gamma}/n_1$ for various absorbers. The value for zero thickness is obtained by extrapolating. The value obtained is $2.45 \times 10^{-3} \pm 2\%$. The source consisted of a thin (about 3 mg/cm^2) film of Mn electroplated on 1 mil silver foil. The small activity of the foil was corrected for in all measurements. There is a slight correction to the value of η_γ because of the reflection of the beta rays by the backing. This correction was estimated as follows. It was found that a 1 mil silver foil absorbs about 20 percent of all the beta rays from the source. We assume that the absorption for the three groups varies [11] as $E^{-1.33}$ and that 80 percent of the absorption of the β_1 is due to back backscattering, and 60 percent in the case of the two soft spectra. The result is not very sensitive to these assumptions. From the curve Fig. 3 it appears that the gamma rays accompanying the soft spectra are counted about three times as efficiently as γ_3 alone. Thus we calculate that the correction due to backscattering is 3 ± 1 percent. Thus we get

$$\eta_\gamma = 2.37 \times 10^{-3} \pm 3\%$$

The beta ray counter was not calibrated because the sources which were used for the cross section determination were strong enough to be counted on the gamma ray counter. They consisted of rolled manganese foil 100 mg/cm^2 thick.

10. Calibration by means of UX_2

Before the calibration by means of the coincidence method was attempted, the counter referred to above as counter B was calibrated by counting a weighed

11) Evans, R. D. - Introduction to the Atomic Nucleus - MIT Lecture Notes.

amount (about 20 mg) of uranium. We assume that the uranium is in equilibrium with UX_2 and that the UX_2 beta rays are the only ones counted. Using the value of 25010 β/sec gm given by Kovarik and Adams [12] of which 1.9 percent is due to 25 [13], we find that there are 12,220 β/sec gm of uranium. Using this value it was found that counter B was 0.260 efficient for UX_2 beta particles. Since these are quite energetic and both source and counter window are thin, it was assumed that absorption corrections were negligible in this case. In the case of Au^{198} corrections were made both for absorption in the window and in the source. These corrections were made from thickness vs counting rate curves obtained in the geometry actually used. In this way an efficiency of 0.236 was found for Au^{198} beta rays. To this we must add the number of conversion electrons, taken to be 6 percent of the beta rays (Section 5). Thus we find $\eta_\beta = 0.250$, in excellent agreement with the value obtained by coincidence measurements (Section 6).

C. FISSION COUNTING

11. Apparatus

Fig. 4 shows a diagram of the ionization chamber used. This chamber was placed in the carbon column about 6 feet from the cyclotron. The cadmium ratio both for indium and for fission detectors was several thousand. The chamber was placed so that the active deposit faced away from the neutron source, the radioactive monitor foils being closer to the source. It is known that the neutron

12) Kovarik and Adams, J. Appl. Phys., 12, 296 (1941).

13) Frisch, O. R., Private communication.

flux is about twice as strong outward from the source as inward. One run was taken in which a gold foil was placed on the back side of the steel high-voltage electrode, between it and the Pt foil supporting the U deposit, in order to detect any possible effect due to absorption by the steel cup. There was no significant difference between the result of this run and others in which the foil was placed on the other side of the cup. The chamber was filled with nitrogen at a pressure of 90 cm Hg. A curve of counting rate vs gain is shown in Fig. 5; the operating gain was 12 mV. The plateau appears quite flat and we assume that virtually every fission particle which emerges from the source is counted.

12. Uranium Samples

Most of the measurements were taken with the enriched sample Mg17B8 whose 25 content was determined by O. Chamberlain to be $(99 \pm 2) \times 10^{-6}$ gm, by comparing the number of slow neutron induced fissions with the number induced in a sample of E10 material.

One run each was taken with the highly enriched (70%) sample E5D, analyzed by Mr. Chamberlain to contain $(7.60 \pm 0.15) \times 10^{-4}$ gm of 25, and with a sample of normal alloy, EN1 whose 25 content was deduced from the total alpha count to be 4.80×10^{-6} gm. The superficial density of all three films was very nearly the same, namely about 0.15×10^{-3} gm of U_3O_8/cm^2. For a film of this thickness we can make a correction for the fraction of the fission fragments which fail to escape from the deposit. This fraction will be $t/2R$ where t is the thickness (in gm/cm^2) of the deposit and R is the range of the frag-

ments in the same units. Using the measurements by Segre and Wiegand [14] we find that the thickness correction of our deposits is (1.8 ± 0.5)%.

D. RESULTS

13. Measurement of $(\sigma_f/\sigma_{Au})_{th}$

The procedure in comparing the two cross sections was as follows: One or two gold foils were placed in the chamber (Fig. 4), close to the 25 foil. In two runs the monitor foils were shielded by other, heavier, gold foils to eliminate any possible effect of resonance neutrons, as indicated in Table I. It is seen that no significant change was observed. In the case of run #4 the shielding was so heavy that it may conceivably have disturbed the neutron flux. Run #6 was made in an aluminum chamber, kindly loaned to us by R. R. Wilson. The plateau of this chamber was not investigated as carefully as that of our steel chamber. The chamber was then exposed in the carbon column for about two hours, during which time sample Mg17B8 gave about 1.6×10^5 fissions. The sample EN1 of normal alloy gave only 4,000 counts.

Two thicknesses of gold leaf were used. One was pure gold leaf of about 10 mg/cm^2, the other was 23 karat, about 5 mg/cm^2. The impurity in the latter was determined spectroscopically to be copper and silver. The short life of the silver activity and the small cross section of Cu allowed us to neglect any effect due to these on the activity but they had to be taken into account in determining the mass of gold used. The leaves were weighed and counted on one or both of the calibrated counters and with or without glass backing. The prob-

14) Segre and Wiegand, LA-64.

able error assigned to the various measurements in Table I depends on the number of foils and the number of independent counts taken. Because the exposure time was only about 2 percent of the mean life of Au^{198}, we can use Eq. (3c) in conjunction with Eq. (2). We write $N_f = n_f T$ for the total number of f counts during the exposure time T. Thus, using M_{25} and M_{Au} to denote the mass of 25 and gold used respectively, we have

$$(\sigma_f/\sigma_{Au})_{th} = 197\, M_{25}\, N_f\, \epsilon_f\, \lambda(1-\tfrac{1}{2}\lambda T)/n' 235\, M_{Au}\, \eta_\beta \qquad (8)$$

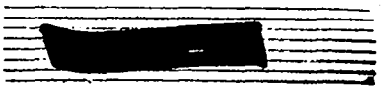
We use $\lambda = (1.78 \pm 0.02) \times 10^{-4}\ min^{-1}$ (Section 2), $\epsilon_f = 0.98 \pm 0.005$ (Section 12). The error in N_f is negligible except in run #5 where it was $\pm 2\%$. The counting error in n', the decay rate after bombardment, varies between 1.5% and 3% in the six runs. M_{Au} was weighed to about $\pm 1\%$. The average error in η_β was taken to be $\pm 4\%$ (Section 7) although it varied somewhat between the several runs, depending on whether one or more foils were counted and on which counter was used. In calculating the probable error of the average (σ_f/σ_{Au}) in Table I account was taken of the fact that the errors in λ, ϵ_f, η_β and (for the first four runs) M_{25} do not average out in the several runs but remain constant. The value of the average is

$$(\sigma_f/\sigma_{Au})_{th} = 5.37 \pm 0.32$$

14. Measurement of $(\sigma_f/\sigma_{Mn})_{th}$

Measurements with manganese were performed exactly as those with gold. The foils were 100 mg/cm^2 and were counted on the gamma ray counter. Because of the shorter mean life of Mn^{56}, Eq. (2) must be used with Eq. (3b). Thus

$$(\sigma_f/\sigma_{Mn})_{th} = 54.9\, M_{25}\, n_f\, \epsilon_f \left[1-\exp(-\lambda T)\right] \Big/ n' 235\, M_{Mn}\, \eta_\gamma \qquad (9)$$



The error in λ is negligible in this case, as is the error in M_{Mn}, because of the greater weight involved. The probable error in η_γ is $\pm$ 3% (Section 9). The other errors are the same as in Section 13. The average, calculated as in the case of gold, is

$$(\sigma_f/\sigma_{Mn})_{th} = 42.1 \pm 2.0$$

15. Calculation of $(\sigma_f)_{kT}$ and radiative capture by 25

In order to calculate the value of σ_f for neutrons of 2200 m/sec velocity we must take into account the deviation of σ_f from the 1/v law found by McDaniel et al [3]. From his results we find $(\sigma_f v)_{kT} = 1.025\ \overline{\sigma_f v}$ $\pm$ 2% for a Maxwellian distribution and room temperature of the neutrons. Thus $(\sigma_f/\sigma_{Au})_{kT} = 5.51 \pm 0.35$ and, using $(\sigma_{Au})_{kT} = (94 \pm 2) \times 10^{-24}$ cm^2 (Section 2), we find $(\sigma_f)_{kT} = (518 \pm 35) \times 10^{-24}$ cm^2.

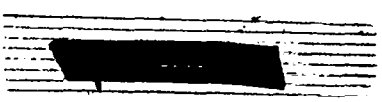
Similarly from the value of (σ_f/σ_{Mn}) given above we calculate, using $(\sigma_{Mn})_{kT} = 13 \times 10^{-24}$ cm^2 $\pm$ 10% (Section 2),

$$(\sigma_f)_{kT} = (561 \pm 60) \times 10^{-24}\ \text{cm}^2$$

or, as an average

$$(\sigma_f)_{kT} = (526 \pm 30) \times 10^{-24}\ \text{cm}^2$$

Here we weight the two values according to the accuracy of the absorption cross sections (i.e. 1:5) rather than the total probable errors since much of the latter, e.g. the error in M_{25}, is common to both determinations. This compares with the value $(645 \pm 16) \times 10^{-24}$ cm^2 for the absorption cross section (Section 1).



The ratio of the two values is

$$(1+\alpha)_{kT} = 1.23 \pm 0.08$$

The excess

$$(\alpha)_{kT} = 0.23 \pm 0.08$$

is presumably due to a competing process, probably radiative capture by 25, or conceivably, by 24.

TABLE I

Run	Sample	M_{25}/μ_5	$(\sigma_f/\sigma_{Au})_{th}$	Position of foil
1	Mg17D8	99	5.27 ± 0.35	Directly under 25 sample
2	"	"	5.39 ± 0.35	In steel cup
3	"	"	5.43 ± 0.35	50 mg/cm^2 gold shield
4	"	"	5.71 ± 0.42	150 mg/cm^2
5	EN 1		5.17 ± 0.50	In cup
6	E5D	760	5.20 ± 0.50	In Al chamber
		Average	5.37 ± 0.32	

TABLE II

Run	Sample	M_{25}	$(\sigma_f/\sigma_{Mn})_{th}$
1	Mg17B8	99	41.6 ± 2.5
2	"	"	42.6 ± 2.5
		Average	42.1 ± 2

TABLE III

SUMMARY OF PROBABLE ERRORS IN INDIVIDUAL RUNS AND IN CALCULATIONS

Quantity	Symbol	± %
Mass of 25	M_{25}	2
Mass of gold	M_{Au}	1
Thickness correction for f foil	ϵ_f	0.5
f count	N_f	negligible
Gold decay constant	λ_{Au}	1
Beta count	n'	1.5 - 3
Counter efficiency	η_β	4
Gold cross section	σ_{Au}	2
25 total cross section	$\sigma_c(25)$	2.5

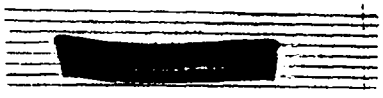
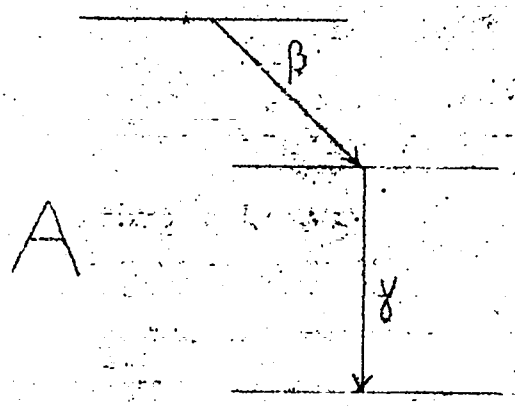
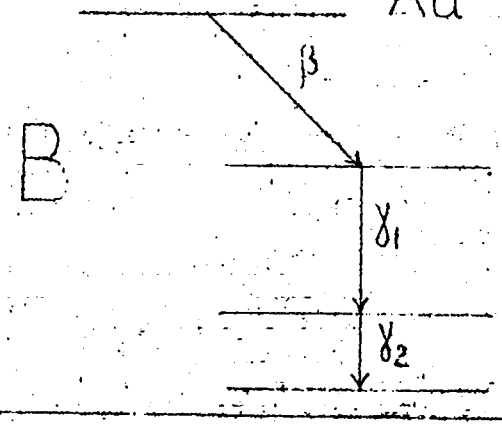


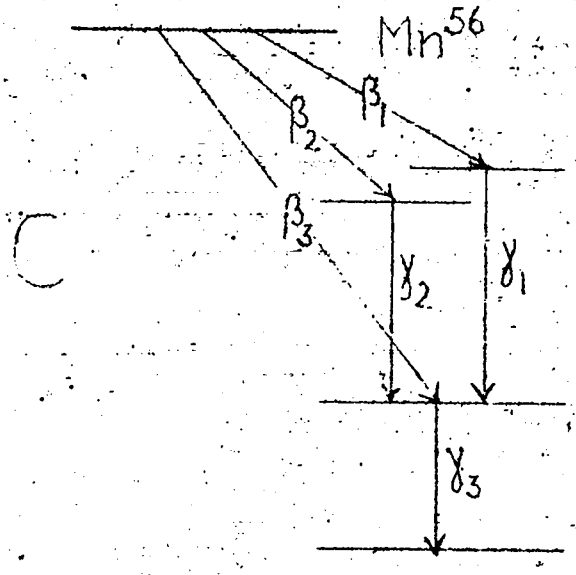
Fig. 1





β : 0.8 Mev
γ1 : 0.41 "
γ2 : 0.12 "

Int. conv. coeff.
$a_1 \simeq 0.05$
$a_2 \simeq 0.3$



β1 : 0.75 Mev
β2 : 1.05 "
β3 : 2.88 "
γ1 : 1.81 "
γ2 : 2.13 "
γ3 : 0.85 "

Rel. Abundance
$f_1 = 0.15$
$f_2 = 0.25$
$f_3 = 0.60$

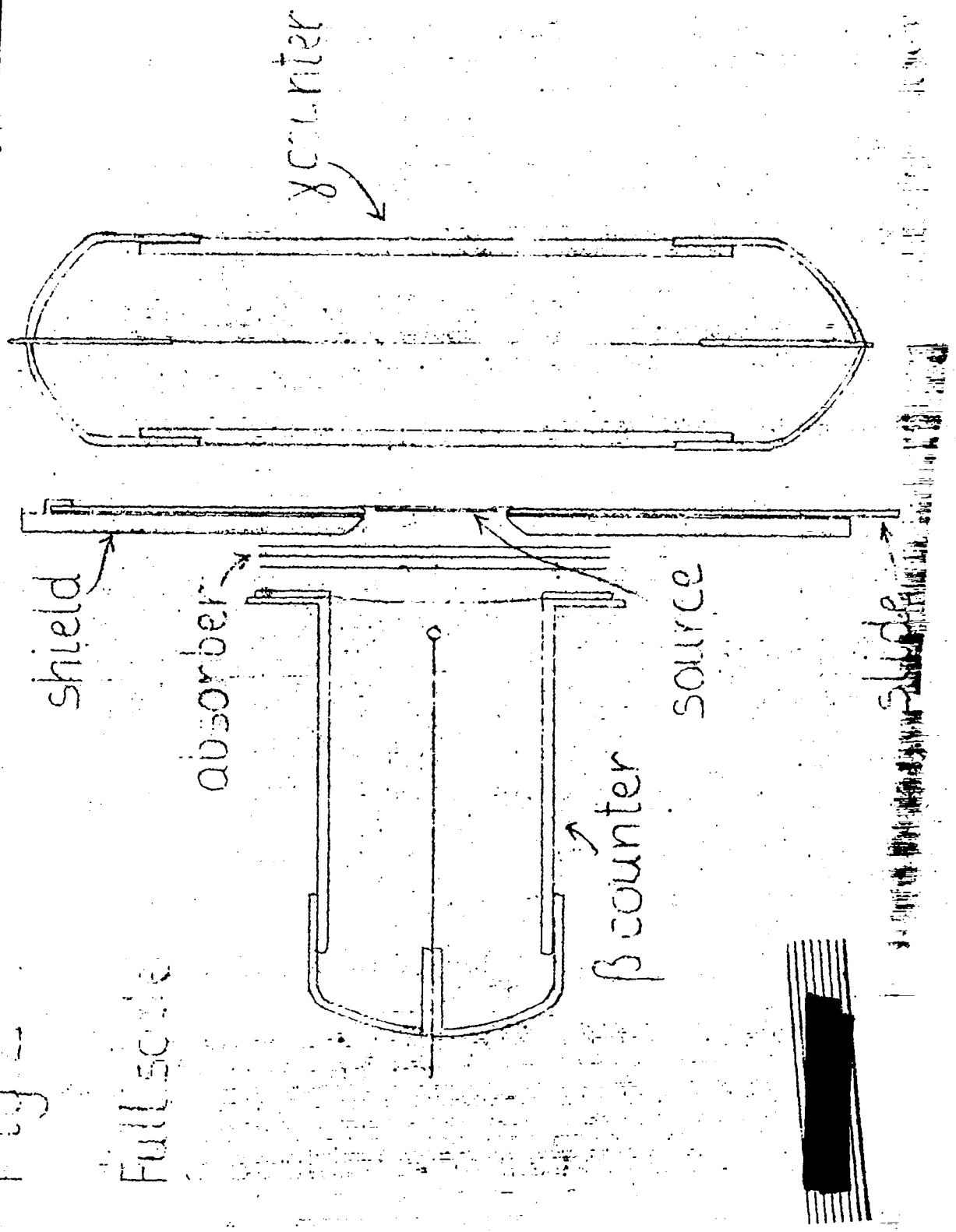
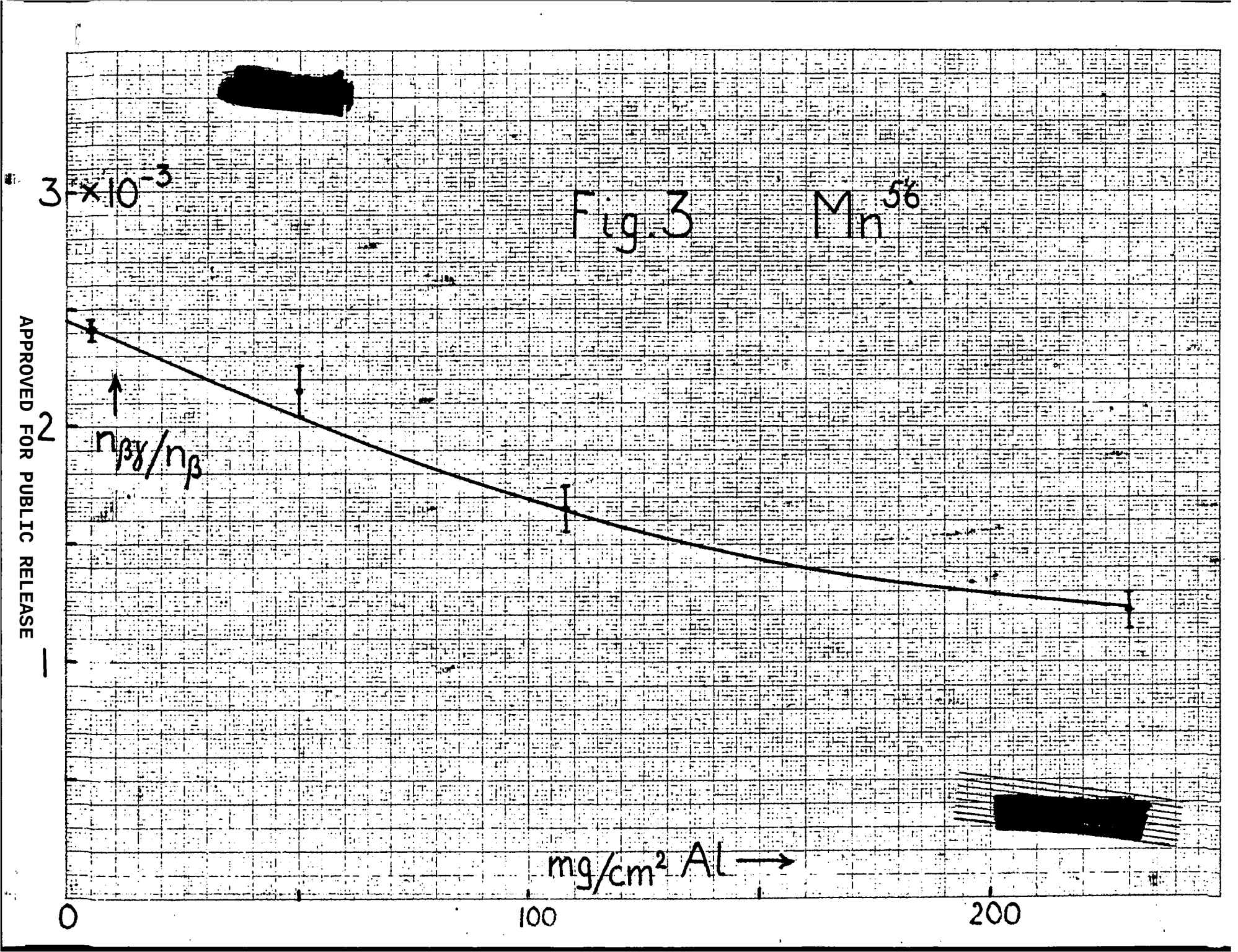


Fig. 2
Full scale



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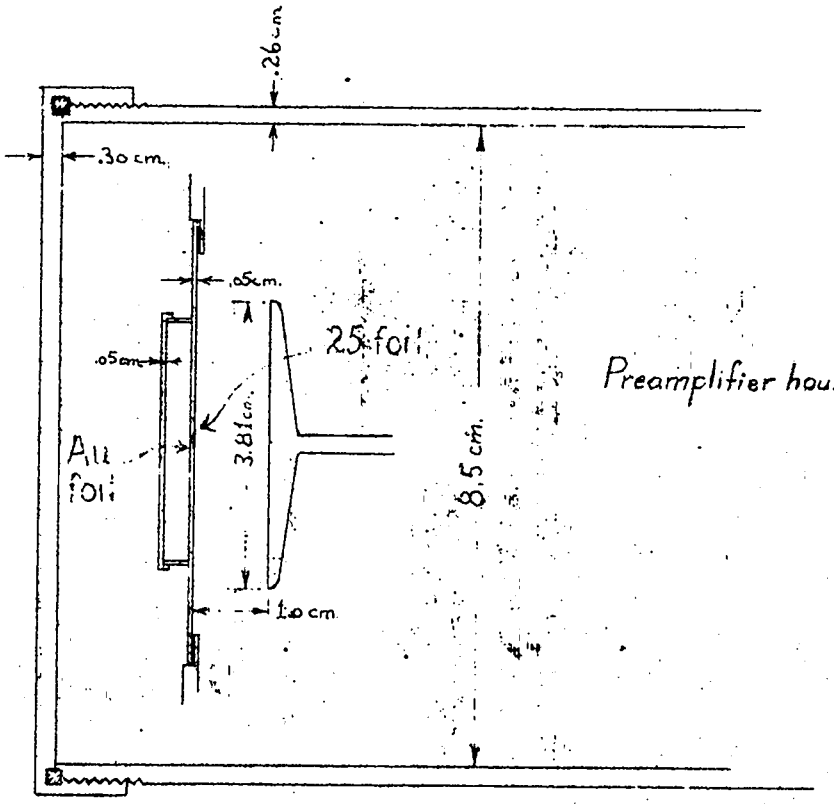
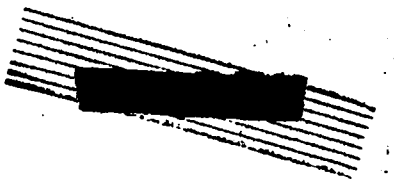


Preamplifier housed here; overall length 29 cm.

Fig. 4

Fission Chamber - Steel
Scale: full size



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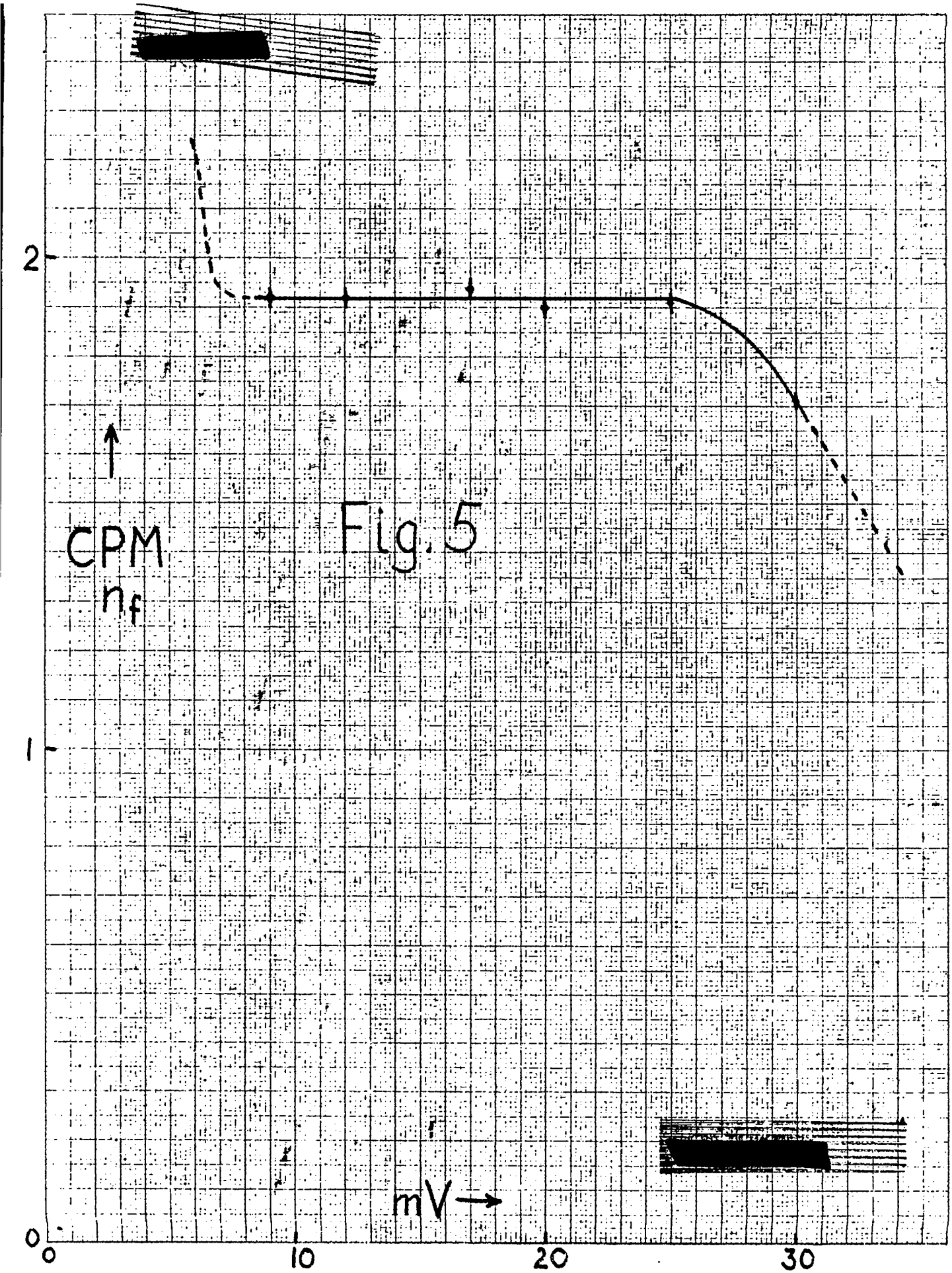

Fig. 5